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EFFECT OF PRESTRAIN UPON ACOUSTOELASTIC PROPERTIES OF CARBON STEEL

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Abstract

Earlier measurements on steels containing different amounts of carbon show that the stress acoustic constants (SAC's), which measure higher-order elastic material properties, are linearly dependent on the amount of ferrite phase in these steels. In order to further characterize the behavior of higher-order elastic properties of carbon steels, the present study investigates the effect of prestrain upon the SAC's of 1016, 1045 and 1095 carbon steels. The SAC's are measured for each of the three alloys after varying amounts of prestrain are produced by tensile loading into the plastic range. The SAC measurements are made in the linear elastic range using small tensile as well as compressive loads. Stress-induced changes in ultrasonic velocity are measured using a pulsed phase locked loop interferometer with resolution of parts in 10^7. Results of this study show that the SAC's measured in tension increase while the SAC's measured in compression decrease as a result of prestrain. The average of these two quantities, however, remains unchanged as a function of the prestrains used in this investigation. This average is found to change linearly with the amount of ferrite phase present in the alloys and confirms previous findings.

1. Introduction

Cold working of many metallic materials results in increased hardness and strength. A work hardened material resists plastic deformation more strongly than the original. The susceptibility of metals to plastic deformation and their property of work hardening is responsible for more of the usefulness of metals than any other property. Earlier measurements [1,2] on steels containing different amounts of carbon show that the stress acoustic constants (SAC's), which measure higher-order elastic material properties, are linearly dependent on the amount of ferrite phase in these steels. The purpose of the present research is to further characterize the behavior of the higher-order elastic properties of carbon steels by examining the effect of plastic deformation on the SAC measurements.

Use of the absolute ultrasonic velocity for measuring residual stress suffers from two major limitations. The first limitation is the uncertainty of the value of ultrasonic velocity at zero residual stress. The second limitation is the sensitivity of the velocity-stress calibration to metallurgical variables which makes it necessary to perform calibration on a specimen of the same material in which the residual stress needs to be measured. The findings reported in this paper may offer a solution to the problem of the sensitivity of the velocity-stress calibration to metallurgical variables such as dislocation density associated with prestrain.

The effect of prestrain on the SAC is investigated in the three AISI alloys 1016, 1045 and 1095. The SAC in specimens of these alloys as a function of prestrain is measured when the stress is applied in tension as well as in compression. The results show that the measured SAC changes considerably as a function of prestrain. It increases when the measurements are done using tensile stress and decreases when the measurements are made in compression. The average, however, is found to be independent of the amount of prestrain in the specimen. The plot of the average of tensile and compressive SAC's vs percent ferrite phase confirms earlier findings in carbon steels.

2. Test Samples

Three carbon steels, namely AISI 1016, AISI 1045 and AISI 1095 are chosen for this investigation. Results of composition analysis are shown in Table I. The table shows that the primary compositional element that varies significantly in these samples is carbon. Figure 1 shows representative micrographs for the three steels before and after prestraining. Comparison of the micrographs of these three carbon steels shows that the microstructure in the alloys is unaltered by prestraining. Figure 1 also helps illustrate that these carbon steels are biphase materials consisting of ferrite and carbide. The white areas in the micrographs represent the ferrite phase with carbon present in solid solution, while the dark areas represent the pearlite structure which consists of 88% ferrite and 12% carbide. One can see from figure 1 that as the carbon content increases the percentage of ferrite phase decreases and the percentage of carbide phase increases.

Test samples used in this study consist of rods 2.54 cm diameter and 20 cm long. The central 7.6 cm of each rod is machined to square cross-section 2.0 cm x 2.0 cm rounding all corners using ASTM standard practices. The surfaces are ground

Steel	C	Ni	Cr	Mn	Mo	S
AISI 1016	.15	.10	.15	.71	.02	.04
AISI 1045	.49	.04	.12	.82	.00	.03
AISI 1095	1.02	.03	.09	.56	.00	.02

Table I Chemical composition of AISI 1016, AISI 1045 and AISI 1095 (weight percentages).

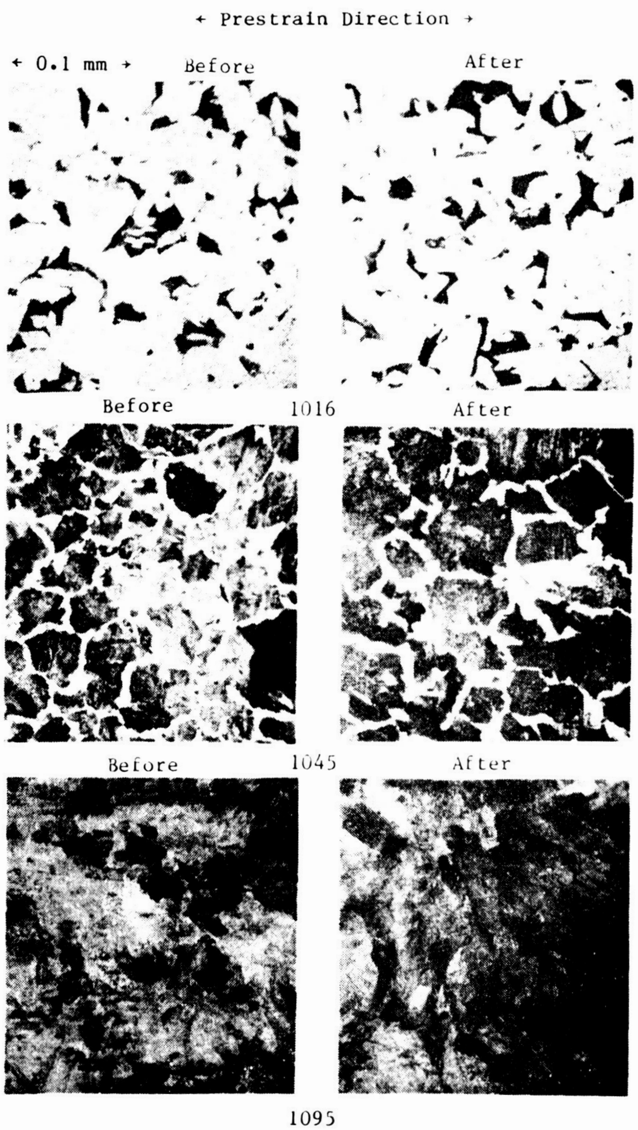

Fig. 1 Microstructure of 1016, 1045 and 1095 carbon steels before and after plastic deformation. Prestrain was applied in the amounts of 4.57% for 1016, 3.92% for 1045 and 1.99% for 1095 and is not seen to change the phase microstructure.

to be smooth, flat and parallel within ±0.005 mm (±0.0002 in) and are lapped using 5 micrometer alumina grit on glass followed by 1 micrometer grit in final preparation for the acoustic measurements.

3. Stress Acoustic Constant

The stress acoustic constants (SAC's) for the steel samples are measured using a pulsed phase locked loop (P^2L^2) system described in detail elsewhere [3]. A block diagram of the P^2L^2 used in this investigation is shown in figure 2. The basis

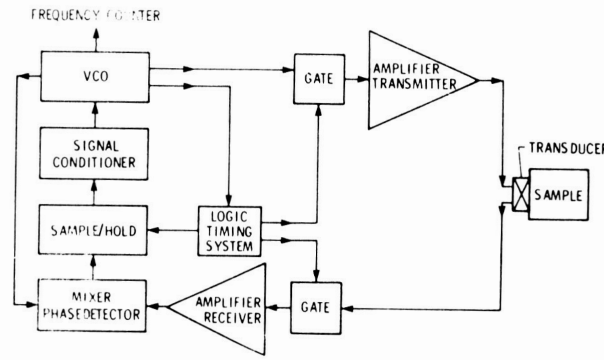

Fig. 2 Block diagram of the pulsed phase locked loop ultrasonic system.

of the measurement is a phase feedback scheme using a voltage controlled oscillator (VCO). The VCO output is gated to produce a tone burst of several cycles to drive a broadband transducer. The returning echo is amplified and phase detected using the VCO as a reference. A logic system samples the phase signal at a preselected point and causes the frequency of the VCO to change until quadrature is achieved. Once locked, the P^2L^2 maintains the quadrature condition with the change in frequency related to the change in sample properties given by [4]:

$$\left(\frac{\Delta F}{F}\right) = \left(\frac{\Delta V}{V}\right) - \left(\frac{\Delta L}{L}\right) \tag{1}$$

where L is the acoustic pathlength in the sample. The normalized change in frequency, $\Delta F/F$, is called the natural velocity derivative in contrast to V, the acoustic phase velocity in the sample. With the natural velocity, one does not have to measure the change in sample length during the measurement.

Figure 3 shows the experimental arrangement for measuring SAC's. In this arrangement the samples are hydraulically gripped and stress is applied using a fatigue loading machine. The load and frequency data are recorded by means of a lab computer on the IEEE-488 bus. The SAC is determined by dividing the change in stress by the change in normalized frequency. Since the SAC tests are run from an electronic 20-second ramp driving the piston of the loading machine, the data represent nearly adiabatic conditions.

Figure 4 shows a typical example of a 1045 steel tensile load SAC run with longitudinal (compressional) waves at 10 MHz propagating

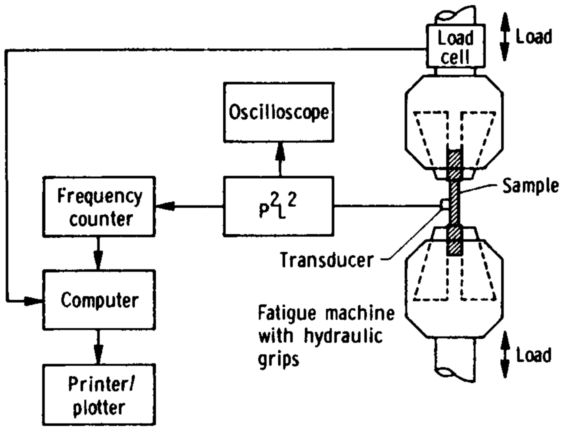

Fig. 3 Diagram of the system for measuring SAC's and applying prestrain. An extensometer (not shown) is used to measure prestrain.

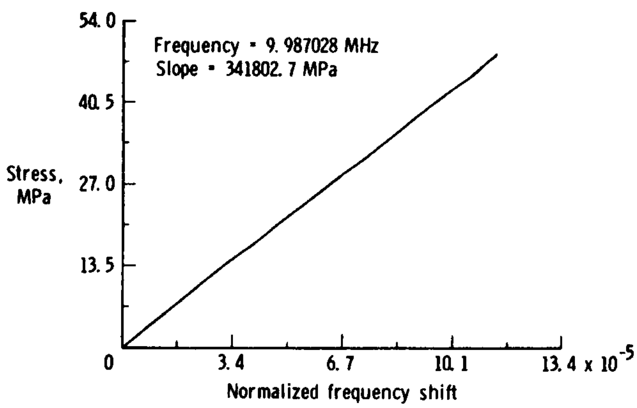

Fig. 4 Normalized frequency shift as a function of applied tensile stress for a typical SAC measurement with transverse ultrasonic propagation. The above figure is for 1045 carbon steel before prestraining.

transverse to the applied load. The slope of the curve is 43.18 x 10^4 MPa which is reproducible within ±1%.

4. Experimental Procedure

In order to study the effect of prestrain on the higher order elastic properties, SAC measurements are made in tension and compression on a test sample of each material after various amounts of prestrain. Figure 5 describes the experimental procedure used for these measurements. The SAC's are first measured in the unstrained sample using small tensile and compressive stresses of about 15% of the yield strength. Permanent deformation of about 0.5% is then applied by tensile loading into the plastic range. The load is then removed leaving the sample prestrained. Prestrain is measured using an extensometer and is checked by measuring the change

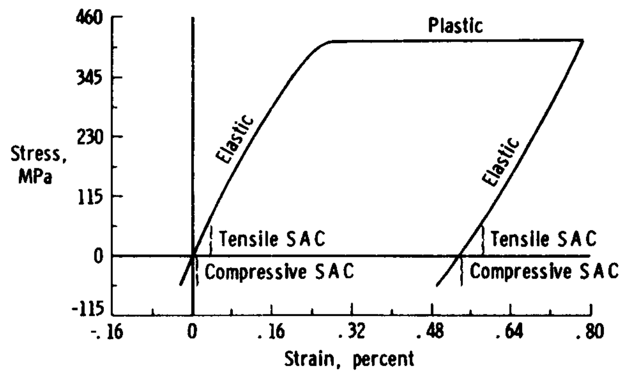

Fig. 5 Experimental procedure consists of measuring the SAC with small tensile and compressive stresses after varying amounts of prestrain.

in distance between lines placed along one edge of the sample. A traveling microscope is used to measure the line spacing before and after prestrain. After plastic deformation, the acoustic surfaces of the test sample are relapped using 5 micrometer alumina grit followed by 1 micrometer alumina grit to eliminate surface irregularities created by prestraining. The acoustic transducer is placed at the same location on the sample and the tensile and compressive SAC measurements are made in the same manner as before. Following the acoustic measurements, the sample is prestrained an additional amount, unloaded and relapped. The SAC is then remeasured at the new prestrain value. This procedure is followed to a prestrain level of 5.25% for 1016, 5.07% for 1045 and 1.90% for 1095 (the 1095 sample fractured at about 2% prestrain preventing further measurements).

5. Results and Discussion

Figures 6, 7 and 8 display the changes in SAC's measured using stress applied in tension as well as in compression as a function of percentage of prestrain for the AISI alloys 1016, 1045 and 1095, respectively. This data shows that prestrain causes the SAC to change in a similar manner in each of the three steels investigated. The SAC's measured using tensile stresses increase with prestrain (except for an initial decrease for 1016 steel) while the SAC's obtained when compressive stresses are applied decrease with prestrain. The figures also show that the difference between the values of SAC's measured in tension and in compression increases as the amount of prestrain is increased and that, at higher values of prestrain, the SAC changes tend to become less pronounced.

Previous research [1,2] has shown the existence of a relationship between the SAC and percentage of ferrite phase in steels. Similar relationships have also been found by Schneiderl et al [5] in aluminum alloys. Figure 9 displays the change in SAC's measured in tension and in

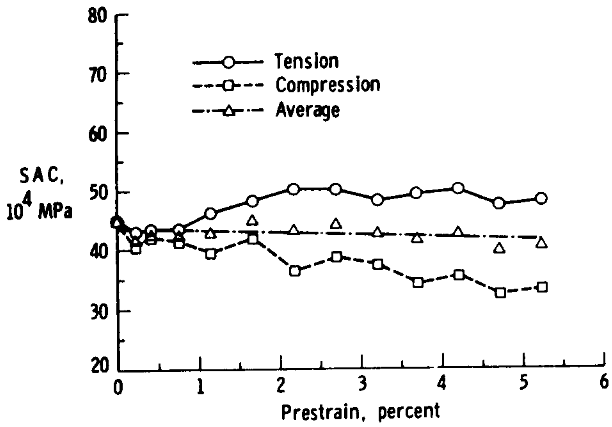

Fig. 6 Experimental results for 1016 carbon steel showing that the SAC measured in tension increases with prestrain while the SAC measured in compression decrease. Note that the average of SAC's measured in tension and in compression is independent of prestrain.

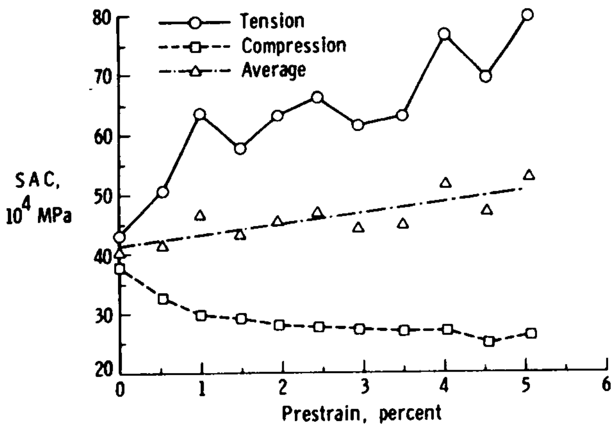

Fig. 7 Experimental results for 1045 carbon steel. Note the similarity of behavior to that of 1016 steel.

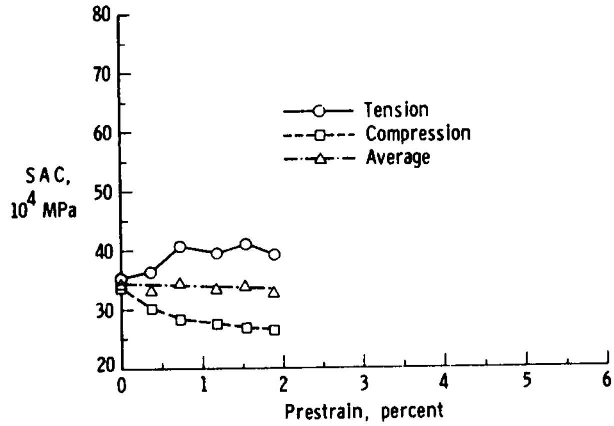

Fig. 8 Experimental results for 1095 carbon steel. Similar behavior to that of 1016 and 1045 carbon steels is observed. This 1095 sample fractured at about 2% prestrain preventing further measurements.

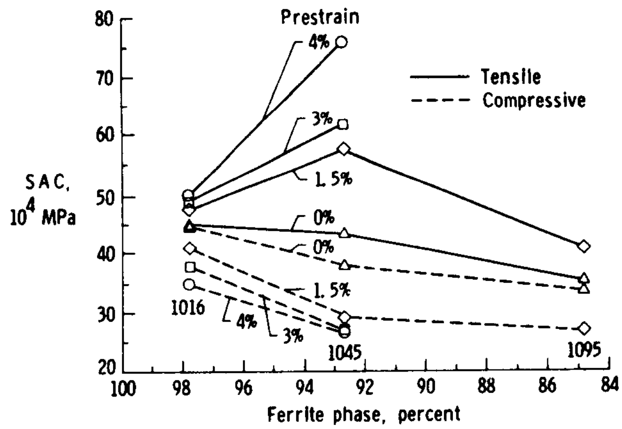

Fig. 9 SAC's measured in tension and compression as a function of % ferrite phase in 1016, 1045 and 1095 carbon steels at four different prestrain levels.

compression as a function of percentage of ferrite phase for values of prestrain of 1.5%, 3% and 4%. Also included in this figure are the values of SAC's obtained before any plastic deformation was applied. The amount of ferrite phase in each of these alloys is calculated using the lever rule and the carbon content in each alloy (Table I). From this data one can see that as the amount of ferrite phase decreases in going from 1016 to 1045, the SAC at constant prestrain increases or decreases according to whether the SAC is measured with stress applied in tension or in compression, respectively. As the amount of ferrite is further decreased by going from 1045 to 1095, the SAC at constant prestrain decreases. The decrease, however, is much larger when the SAC is measured with the stress applied in tension. The behavior of SAC's with prestrain shown in figure 9 may be explained in terms of the dislocation contribution to the measured stress acoustic constant. It is well established that plastic deformation increases the dislocation density in metallic materials [6]. Some of these dislocations are immobile due to strong pinning points such as vacancies, interstitials and other dislocations, but a small percentage of these dislocations are mobile even at stress levels well below the elastic limit [7]. The movement of mobile dislocations will influence the sound velocity which, in turn, influences the value of the measured SAC [8]. With no dislocation contribution, the measured SAC will be due only to the lattice contribution to the higher order elastic constants [9]. The effect of mobile dislocations on the ultrasonic velocity differs according to the direction in which these dislocations move when the stress is applied in tension or in compression [10]. Accordingly, the contributions of these mobile dislocations to the measured SAC will be positive or negative according to whether the stress used in measuring the SAC (within the elastic range) is applied in tension or in compression. In a plastically deformed specimen, the relative change in ultrasonic velocity with stress due to dislocations, $(\frac{\Delta V}{V})_D$, will then be added to or subtracted from that of the lattice, $(\frac{\Delta V}{V})_L$, according to whether the stress is applied in tension or in compression. Therefore, the average of the SAC's measured with stress applied in tension and with stress applied in compression is that of the lattice which does not vary with prestrain. There is also a possibility that the effect of prestrain on the SAC has a magnetic domain contribution.

Figure 6, 7 and 8 include the averages of the SAC's measured using applied tensile and compressive stresses at the various amounts of prestrain in the alloys 1016, 1045 and 1095, respectively. Also included in each of these figures is the linear least square fit to the average SAC values. From this one can see that in both AISI 1016 and 1095, the average values of SAC's measured in tension and in compression remain unchanged as a function of prestrain. In the case of AISI 1045, however, the average increases by about 20% within the 5% prestrain used in this alloy. This increase in the SAC for 1045 steel suggests that the average of the SAC's measured in tension and in compression can include a small amount of dislocation contribution and does not exactly equal to the lattice SAC. However, the error in determining the lattice SAC using the average of SAC's measured in tension and in compression is much less than that obtained from values measured using tensile or compressive stress alone and suggests the use of the average value of the SAC in determining residual stresses.

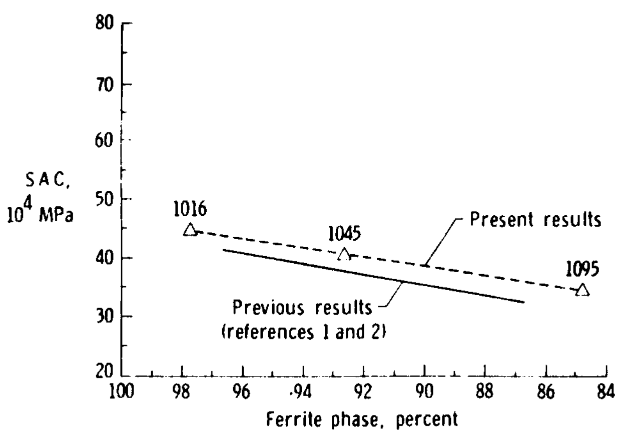

Fig. 10 SAC as a function of % ferrite phase in carbon steels from previous and present studies (before prestraining). Results of present study agree with previous findings.

Figure 10 compares present results to previous findings. This figure presents the change in the average SAC determined from figures 6, 7 and 8 as a function of the percent of ferrite phase in the alloys 1016, 1945 and 1095. Also included in figure 10 are the SAC values obtained previously for carbon steel alloys measured at zero prestrain using stress applied in tension. From figure 10 one can see that the values of SAC determined from the average of SAC's measured in tension and compression at various prestrains is about equal to those obtained previously at zero prestrain. Figure 10 also shows that the average SAC behaves in a similar manner to that obtained in previous experiments, i.e. the SAC decreases as the amount of ferrite phase decreases. This confirms previous findings [1,2] of a linear relationship between SAC's and percent ferrite phase in carbon steels.

6. Conclusions

Higher-order ultrasonic properties have proven to be very significant in materials characterization. Previous research showed that higher-order elastic properties of steel are influenced by carbon content. The present study shows that prestrain also influences the higher-order elastic properties of carbon steel. From the present study several conclusions can be drawn: 1) The measured SAC in the steel alloys 1016, 1045 and 1095 depends on whether the stress used in determining this quantity is applied in tension or in compression. 2) The SAC's measured with stress applied in tension increase with prestrain, while the SAC's measured using compressive stress decrease with prestrain. 3) The average of SAC's measured in tension and in compression in alloys 1016 and 1095 are independent of prestrain. The average SAC for 1045 steel increases by about 20% for a prestrain of 5 percent. These averages are believed to represent the intrinsic lattice contribution to the SAC. 4) The plot of the average SAC as a function of % ferrite phase is linear and agrees with earlier findings.

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